**PCT** WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

**(51) International Patent Classification** 6 **:**
**H01T 1/02**

**A1**

**(11) International Publication Number:** **WO 99/23735**

**(43) International Publication Date:** 14 May 1999 (14.05.99)

**(21) International Application Number:** PCT/IB97/01394

**(22) International Filing Date:** 5 November 1997 (05.11.97)

**(71) Applicants** *(for all designated States except US)*: KIM, Andrew [US/US]; 36–13 21st Avenue, Astoria, NY 11105 (US). GLOBLEX TECH. INC. [–/–]; Caledonian House, P.O. Box 265, George Town, Grand Cayman (KY).

**(72) Inventors; and**
**(75) Inventors/Applicants** *(for US only)*: LI, Am, Gil [KP/KP]; Segori dong, Potonggang District, Pyongyang (KP). KIM, Young, Su [KP/KP]; Segori dong, Potonggang District, Pyongyang (KP).

**(74) Common Representative:** KIM, Andrew; 36–13 21st Avenue, Astoria, NY 11105 (US).

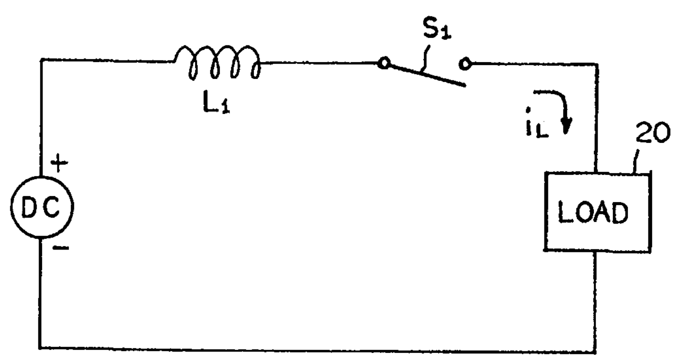
**(81) Designated States:** AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

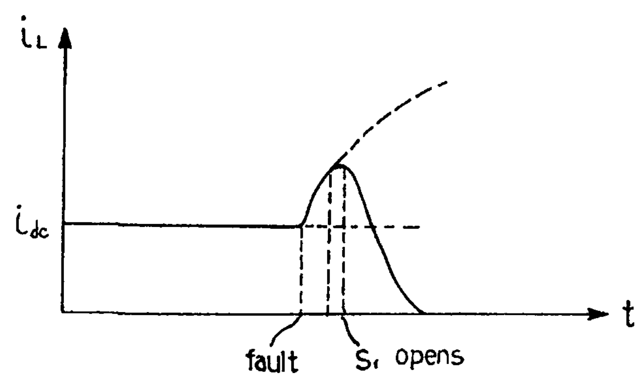
**Published**
*With international search report.*

**(54) Title:** METHOD AND APPARATUS FOR USING AN ARC–DIPOLE IN AN OPENING SWITCH TO GENERATE A POWER PULSE

**(57) Abstract**

A method and apparatus for using an arc–dipole in an opening switch to generate a power pulse to a load from a storage device. A power pulse is delivered to the load over a time which is short as compared to the energy storage time. A magnetic field may be used to enhance the arc–dipole and thereby shorten the opening time. A pulse–voltage source is imposed across the electrodes or spark gap in order to form and then extinguish the arc dipole. Preferably, a pre–charged capacitor may be used as a source for the pulse current. When the arc dipole is extinguished, charged particle free spaces are formed around the surface of the electrodes which serves as a reliable dielectric thereby inhibiting re–ignition. The invention may be used to produce pulses to a load at a repetition rate on the order of about 1 to 1,000 bps.



***FOR THE PURPOSES OF INFORMATION ONLY***

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **AL** | Albania | **ES** | Spain | **LS** | Lesotho | **SI** | Slovenia |
| **AM** | Armenia | **FI** | Finland | **LT** | Lithuania | **SK** | Slovakia |
| **AT** | Austria | **FR** | France | **LU** | Luxembourg | **SN** | Senegal |
| **AU** | Australia | **GA** | Gabon | **LV** | Latvia | **SZ** | Swaziland |
| **AZ** | Azerbaijan | **GB** | United Kingdom | **MC** | Monaco | **TD** | Chad |
| **BA** | Bosnia and Herzegovina | **GE** | Georgia | **MD** | Republic of Moldova | **TG** | Togo |
| **BB** | Barbados | **GH** | Ghana | **MG** | Madagascar | **TJ** | Tajikistan |
| **BE** | Belgium | **GN** | Guinea | **MK** | The former Yugoslav Republic of Macedonia | **TM** | Turkmenistan |
| **BF** | Burkina Faso | **GR** | Greece | | | **TR** | Turkey |
| **BG** | Bulgaria | **HU** | Hungary | **ML** | Mali | **TT** | Trinidad and Tobago |
| **BJ** | Benin | **IE** | Ireland | **MN** | Mongolia | **UA** | Ukraine |
| **BR** | Brazil | **IL** | Israel | **MR** | Mauritania | **UG** | Uganda |
| **BY** | Belarus | **IS** | Iceland | **MW** | Malawi | **US** | United States of America |
| **CA** | Canada | **IT** | Italy | **MX** | Mexico | **UZ** | Uzbekistan |
| **CF** | Central African Republic | **JP** | Japan | **NE** | Niger | **VN** | Viet Nam |
| **CG** | Congo | **KE** | Kenya | **NL** | Netherlands | **YU** | Yugoslavia |
| **CH** | Switzerland | **KG** | Kyrgyzstan | **NO** | Norway | **ZW** | Zimbabwe |
| **CI** | Côte d'Ivoire | **KP** | Democratic People's Republic of Korea | **NZ** | New Zealand | | |
| **CM** | Cameroon | | | **PL** | Poland | | |
| **CN** | China | **KR** | Republic of Korea | **PT** | Portugal | | |
| **CU** | Cuba | **KZ** | Kazakstan | **RO** | Romania | | |
| **CZ** | Czech Republic | **LC** | Saint Lucia | **RU** | Russian Federation | | |
| **DE** | Germany | **LI** | Liechtenstein | **SD** | Sudan | | |
| **DK** | Denmark | **LK** | Sri Lanka | **SE** | Sweden | | |
| **EE** | Estonia | **LR** | Liberia | **SG** | Singapore | | |

# Method And Apparatus For Using An Arc-Dipole In An Opening Switch To Generate A Power Pulse

## Background

### 1. Field of the Invention

The present invention relates to a method and apparatus for producing an energy pulse over a comparatively short time period. More specifically, the present invention relates to a method and device for delivering a power pulse to a load from an energy storage device where the power pulse is delivered to the load over a time which is short as compared to the energy storage time.

### 2. Description of the Related Art

Many applications, such as metal forming, high temperative welding, radar modulators, inertial confinement fusion, microwaves, lasers, flash x-rays, plasma furnaces, plasma torches, electron beam torches, sewage treatment by ozone production and others, require pulsed power sources.

Such power sources put special demands on switching systems, especially where high power switching is involved. Pulsed power systems capable of delivering a single pulse of over 100TW have been reported. See, generally Advances In Pulse Power Technology, Vol. 1, Opening Switches, Editors: A. Grenther et al., Plenum Press (1987).

However, the available technology has not provided opening switch having reliably repeatable switching characteristics, which as would be required when switching inductive energy sources.

The purpose of an opening switch is to stop the flow of current into a circuit branch. To accommodate current interruption, the switch must be able to force the current to transfer from the switch to a load and to withstand the voltage generated by the divided current flowing through the load.

Opening switches may be used, for example, to provide fault (i.e. short-circuit) current protection, to "sharpen" the current pulse from a capacitive discharge or CD system, or enable the transference of inductively stored energy.

In the first of the above examples, a typical opening switch operates much in the sense of a conventional fuse by interrupting current to the load. See Figs. 1A and 1B. This is the mode and manner of operation of the switch described in applicant's co-pending application Serial No. PCT/1B97/00375, filed April 8, 1997.

A typical prior art situation in which an opening switch must carry a relatively large current when closed, and on command, transfer that current into a load, is illustrated in

Figs. 2A and 2B. The opening switch $S_1$ is normally closed. Near the peak current ($I_{L1}$) the switch opens causing the capacitor $C_1$ to discharge through the load.

A standard inductive energy storage system, such as might be used to deliver a single large pulse or a train of pulses to a load, is depicted in Fig. 3A. Energy is transferred from the inductor $L_1$ to the load each time the opening switch $S_1$ operates.

As explained more fully in *Inductive Energy Storage Circuits and Switches*, E.M. Honig, Advances In Pulsed Power Technology, Vol. 1 at pp. 1-49 there are two basic types of opening switches, direct interruption and zero current. As will be appreciated by the artisan, the type selection is based on whether the voltage which forces the current to transfer out of the switch is developed internally or externally of the switch and upon system characteristics.

Direct interruption switches are switches which can develop the transfer voltage internally, e.g., by an increase in switch impedance. Examples of this type of opening switch are circuit breakers, fuses (e.g., fusible metal links), and diffuse discharge switches where the switch medium is an externally sustained discharge (see Diffuse Discharge Opening Switches, K.H. Schoenback et al., Advances in Pulsed Power

Technology, Vol. 1, Opening Switches, Planum Press 1987 at pp 49-91.

Current zero switches achieve current interruption by means of an external voltage source which drive the switch current to zero and thereby allow the switch to open. Such switches may be used in AC systems which have natural current zero twice per cycle or DC circuit having an auxiliary zero current circuit. Examples of such switches include thyristors, vacuum switches, thyrotrons and plasma switches which utilize an electron beam to maintain the switch closed.

The present invention is applicable to both types of opening switches and, relative to prior art opening switches, is inexpensive, easy to manufacture and maintain and has a low energy consumption characteristic, i.e. is efficient.

The present invention utilizes a previously unknown physical effect created in an ionized gas discharge e.g., a plasma, to extinguish an arc.

Specifically, as detailed in applicant's above referenced copending application, applicant has observed that a quasi-neutral arc column may be reformed into an arc column having a characteristic electric dipole form (hereinafter called an "arc-dipole") when the arc voltage is increased from the initial current to a much higher current within a time period

much shorter than the characteristic relaxation time of the arc plasma. The arc plasma relaxation time, $\tau$, is the time required for an arc discharge to transition between a first steady state to a second steady state in response to the imposition of a voltage across the terminals between the arc is struck. If a strong axial magnetic field acts on the arc at the same time, an arc-dipole having an even larger charge gradient is formed.

As used herein, the term "arc-dipole" means a plasma column, where one end region of the column has an excess of positive ions ($+q_d$), while the other end region has an excess of negative electrons ($-q_d$) and the middle region of the column remains quasi-neutral. This is best seen in Fig. 6. An arc may be referred to as an arc-dipole when the distance ($l_d$) between the charge centers of the arc is much longer than Debye's length of the arc plasma. The arc-dipole is plasma in an unstable state. After it is formed, the arc-dipole is destroyed by contraction of the arc length and by Coulomb scattering of ions at the above noted end regions of the arc-dipole.

The existence of an axial magnetic field forms arc-dipole having a greater charge gradient $g_d$. A strong axial magnetic

field also increases the characteristic relaxation time, $\tau$, of the arc plasma.

The creation and control of an arc dipole in an arc forms a basis of the arc extinction method and apparatus of the present invention.

The existence of an arc dipole in a plasma is counter-intuitive in the sense that a plasma, which is ionized gas, is a conductive medium which supports an arc current; it is not a dielectric. However, applicant has found that under certain circumstances the creation of a plasma column having a positively charged region and a negatively charged region separated by a quasi-neutral region is possible, even though unstable, and that such a state can persist over a finite period of time. In that regard, it should be noted that the total or net charge of the plasma column, including the positive and negative charged regions as well as the quasi-neutral region, remains essentially zero.

Applicant's method makes use of the above instability to extinguish an arc maintained between normally open switch contacts. In fact, the more unstable the arc becomes, the easier it is to extinguish. In order to sustain itself, a plasma must maintain a flow of current through it, i.e., must be stable.

However, once a dipole state is created, the Coulomb forces -- which tend to draw the charged regions together thereby axially contracting the arc -- are great. At the same time, the Coulomb forces tend to cause the charges within each of the positively and negatively charged regions apart, which tends to explosively scatter the charged particles in the charged regions away from the conductive terminals; this force is found to be greater in the positively charged region than in the negatively charged region. Acting together, these forces effectively extinguish the arc in a very short time; i.e., on the order of about 10 μ seconds or less.

In order to form an arc-dipole, a pulsed source, having a voltage much higher than the arc voltage, should be imposed across the arc. It is convenient to use a pre-charged capacitor as a pulse current source although other pulsed sources capable of delivering a current pulse to the arc can be used. When a capacitor is used, the dielectric breakdown voltage and size of capacitor are chosen commensurate with the voltage of the power source and current of the arc.

The rise time of current pulse should be far shorter than the characteristic relaxation time of the arc plasma. Preferably, the current pulse has a very fast rise time, on the order of 1's or at most 10's of μ seconds. Using the

present invention switching times on the order of 1's or 10's of μ seconds may be achieved.

Methods of creating an artificial zero current in an arc are already known. See e.g., A.N. Greenwood and T.H. Lee, IEEE Trans., Vol. PAS, 91, July-Dec. 1972, pp 1570-1574. Also see *Inductive Energy Storage Circuits and Switches*, E.M. Honig from Advances In Pulsed Power Technology, Plenum Press (1987) at pp. 9-42. However, such techniques differ from the present arc dipole methodology.

In the prior art method, an artificial zero-current is made by discharging the current from a pre-charged capacitor so as to cause a current flow in a direction opposite to the initial arc current (the so-called "commutation principle").

In contrast, the method of the present invention results in an absolute value of the total current, i.e., the sum of the initial arc current and the pulse current (e.g., the discharge current from a capacitor) which is far greater than the absolute value of the initial arc current.

The present invention further differs from prior methods in regard to its dielectric recovery characteristics. In the prior method, even thought the current is artificially made zero, an ionized gas column remains where the plasma had been between the contacts, giving rise to the distinct possibility

of arc reignition when a voltage is again applied to the residual plasma column. In other words, in comparison with the present invention the prior method exhibited relatively poor dielectric recovery characteristics.

In the present invention, a charge-particle-free space is formed around the surface of the contacts (or auxiliary electrodes) when the arc column contracts and the positive ions in the arc-dipole are explosively scattered. To a lesser extent, the same is true of the negative ion region. Thus, a charged-particle-free space is formed around the surface of the contacts (or auxiliary electrodes). This space provides reliable insulation. This good dielectric recovery characteristics is one of the important advantages of the present method and apparatus.

Magnetic fields effect the process of forming the arc-dipole. If a magnetic field acts simultaneously on the arc, i.e., with the electric field, an arc-dipole having a larger charge gradient will be formed. Therefore, a magnetic field is also preferably used in connection with the present invention. At present, there are several known ways of establishing such a magnetic field. See for instance, Yanabu S., Tsutsumi T., Yokokura R. and Kaneko E., Proceedings of

13th International Symposium on Discharges and Electrical Insulation in Vacuum, 1988, pp 131-137.

In one exemplary device according to the present invention, a spiral groove structure is preferably formed on the side surface of a cylindrical member associated with a contact piece in order to form such a magnetic field. The surface current along the turns of the spiral groove structure, which is preferably in the form of a screw blade, is used to produce the magnetic field.

The present invention also provides a way for combining the arc dipole plasma extinction method with existing opening switch methods, for instance, the spiral arc. An important difference between the present invention and the spiral arc, as shown for instance in U.S. Patent No. 4,560,848, is that in the present invention, a pair of metal plates or auxiliary electrodes, which are connected to the pulse voltage source, are installed inside of the main switch contact pieces and a spiral groove structure is used in the contact piece(s) to provide a transverse magnetic field.

The present invention is also different from the prior art diffuse discharge opening switches which rely, for example on a controlled electron beam or other radiation to create a diffuse discharge which is used to ionize a gas and thereby

render it conductive in that no controlled external sources of radiation are required, which are not only expensive but also impose about a 50% efficiency penalty and which suffers from the reignition danger discussed above. In this application a spark gap is used.

**Summary Of The Invention**

It is an object of the present invention to provide an improved method of providing power pulses using an arc-dipole in which the arc-dipole is formed by an electric field (or by an electric field combined with a magnetic field) imposed on an arc produced between a pair of normally open electrodes (or spark gap) whereby the arc may be rapidly extinguished by creating an unstable arc-dipole.

Since the arc-dipole is in an unstable plasma state, it will, if created under the above circumstances, essentially instantly (in the range of from within several μ seconds to sub μ second) contract in its axial direction while expanding in its radial direction, while simultaneously the charged particles in the end regions of the arc-dipole are explosively scattered thereby destroying the arc-dipole and extinguishing the arc. As a result, a charged-particles-free space is formed around surface of the electrodes, which space serves as dielectric medium.

The greater the charge gradient of the arc-dipole (i.e., the charge per unit length), the more unstable it is. The use of an electric field together with an axial magnetic field forms an arc-dipole having a large $g_d$ (charge gradient) as compared to an arc dipole formed under the same conditions but using only an electric field.

It is another object of the invention to provide an opening switch based on above arc extinction method.

In one embodiment an opening switch is provided, using only an imposed electric field to produce pulses to a load at a repetition rate an the order of about 1 to 1000 pps.

In another embodiment, an opening switch is provided using both an imposed electric field and a magnetic field to produce pulses to a load at a repetition rate exceeding about 100 pps.

According to a first aspect of the invention, a method for delivering pulsed power to a load is provided. The method comprises extinguishing an electrical arc struck in the gap between two electrodes which is traversed by a current, preferably a DC current. A current pulse is injected into the electrical arc in order to substantially increase the absolute current value well beyond that of the initial arc current. The injected current pulse has a rise time shorter, and

preferably much shorter than the characteristic relaxation time of the arc plasma.

The current impulse may, for example, be provided by a capacitor discharge. The current impulse may be injected into the arc at the electrodes or using auxiliary electrodes positioned within the arc region.

According to a second aspect of the invention, an opening electrical switch having normally open first and second electrodes is provided in order to respectively interrupt a current. The switch further comprises means for injecting a current pulse into the arc subsisting between the electrodes, in order to substantially increase the absolute value of the arc current; the current pulse having a rise time shorter than the characteristic relaxation time of the arc plasma.

Additional objects, advantages and novel features of the invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art upon examination of the following or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

## Brief Description Of The Drawings

The accompanying drawings, which are incorporated in and form a part of the specification, illustrate various embodiments of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

Figs. 1A and 1B are explanatory depictions of the current flow to a load in a series switched inductive circuit.

Figs. 2A and 2B are explanatory depictions of the current flow to a load in a parallel switch LC circuit.

Figs. 3A and 3B are explanatory depicts of the current to a load in a parallel switch inductive circuit with a repetitively cycled switch.

Figs. 4A, 4B and 4C depict various embodiments of opening switch circuits embodying the present invention.

Fig. 4D depicts a variation on the embodiment of FIG 4A in which the load is a furnace and pulsed energy at a high frequency is supplied to the load.

Fig. 5A is an exemplary pulse power output waveform.

Fig. 5B is a depiction of the arc current in the opening switch.

Fig. 6 depicts a model of an arc-dipole.

Figs. 7A and 7B illustrates an embodiment of a switch according to the invention of the handling of medium AC or DC

voltages, for respectively imposing axial and transverse magnetic fields on an arc dipole.

Fig. 8A illustrates the structure of a contact having a screw thread for producing a magnetic field.

Fig. 8B is a cross section of the contact of Fig. 8A.

Fig. 9 illustrates another embodiment of the invention, particularly useful for high and medium voltages, in which an arc-dipole creating structure is combined with a spiral arc opening switch structure.

## Detailed Description

Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings.

The arc extinction method of the present invention is based on the formation of an arc-dipole within the arc produced between a pair of normally open contacts. The method uses electric and preferably magnetic fields to form the arc-dipole. The arc-dipole thus formed is unstable, which extinguishes the arc.

The theory of formation of an arc dipole will now be explained with reference to Fig. 6. As is known, the diameter of an arc column is determined by the magnitude of arc current flowing through it. The higher the current, the larger the

diameter of arc column. This is because the current density of an arc is almost constant in its steady state.

If a current much larger than the arc current (an overcurrent) is caused to flow through the arc by imposing a high voltage (i.e., a voltage much larger than the arc voltage) across the arc and if the time of the voltage increase is longer than the characteristic relaxation time of arc plasma, the diameter of arc column simply expands to allow for the flow of the overcurrent and the arc column remains in a stable state. In this case, the arc column remains generally homogeneously quasi neutral throughout.

However, if the rise time of voltage is far shorter than the characteristic relaxation time of the arc plasma, it is believed that a large number of electrons are caused rapidly flow from the arc **12** into the contact corresponding to positive pole **10**, and also, a large number of electrons are caused to flow into the arc **12** from the other (i.e., negative pole) electrode **20**, in order to accommodate the increased voltage. In the middle region of the arc **14**, the flow velocity of electrons is slower than the flow velocity at the ends of the arc column, since the diameter of the arc column has not yet expanded correspondingly. As a result, one end region of the arc column **16** becomes positively charged with a

charge of $+q_d$, while the other end region **18** becomes negatively charged, with a charge of $-g_d$, and the middle region **14** remains quasi neutral. This state of affairs defines an arc-dipole.

The arc-dipole is a plasma in an unstable state. The average charge gradient of the arc-dipole is:

$$g_d = q_d/l_d \qquad \text{(e.g. 1)}$$

where $q_d$ is the absolute value of the charge at one end of the arc-diploe and $l_d$ is the distance between centers of two charged regions, **16** and **18**. The charge gradient $g_d$ is important quantity that characterizes instability of the arc-dipole. The greater the $g_d$, the more unstable the arc-dipole. This means that the larger the value of $g_d$, the easier it is to extinguish the arc.

As alluded to above, in the arc-dipole, the following two physical processes are believed to take place simultaneously resulting in the destruction of the arc.

First, the arc-dipole **12** rapidly contracts as a result of the strong electrostatic attraction force between its two charged regions **16** and **18** and active deionization takes place in the middle region **14**. At this time, the diameter of the arc column expands. Second and simultaneously, the positive ions in the end region **16** are explosively scattered by electrostatic repulsion force between the positive ions. A

similar, but weaker process takes place at the negative region **18** of the arc-dipole. At this time, a charged-particle-free space is formed around the surface of the electrodes **10** and **20** (and in particular, at the surface of the electrode **10** corresponding to positive pole). This space serves as an dielectric medium which interrupts arc current. As a result, the arc dipole are extinction method results in excellent dielectric recovery characteristics.

A magnetic field is preferably applied to the arc in order to form an arc-dipole having a larger value of $g_d$. The reason that a large gradient arc-dipole is formed more easily in presence of appropriate magnetic filed is as follows:

When a high voltage is imposed across the arc, an arc-dipole is formed, but the diameter of the arc column has not yet expanded so as to allow for the flow of a large current corresponding to the high voltage. The axial magnetic field constrains the expansion of the diameter of the arc column. Thus, the characteristic relaxation time of the arc plasma becomes longer.

This means that for a given pulse electrical source, the use of a magnetic field makes it possible to form an arc-dipole having a larger value of $g_d$. For example, where a capacitor discharge is used to supply the voltage for

injecting a current pulse through the arc, if a magnetic field is applied, the size of the capacitor used can be decreased. In fact, it has been found that if a strong magnetic field acts on the arc, the size of the capacitor may be reduced, in some instances by more than half.

In order to reliably extinguish the arc produced between the electrodes **10** and **20**, a high enough voltage should be imposed across the arc in the presence of an axial magnetic field, thus forming the arc-dipole with a sufficiently large value of $g_d$.

In the embodiment of the invention described below in connection with Fig. 4A, a pre-charged capacitor $C_1$ is used as an pulse electric current source in order to form the arc-dipole.

The charging voltage and size of the capacitor are determined by the voltage across the arc and the current through the arc.

In arc extinction procedure according to the present method will now be described with reference to Fig. 4A.

1. With the switch $S_1$ in position "**a**", the condenser $C_1$ is pre-charged to the voltage of the electric power source $PS_2$.

2. With the switch $S_1$ in position b the pre-charged condenser $C_1$ is discharged through the arc produced between the

electrodes **1, 2** of the opening switch **OS** after the circuit is open. At this time, the direction of the discharge current from the capacitor $C_1$ can be either in the same direction as, or the opposite direction to, the direction of the arc current. This is because the charged voltage of capacitor $C_1$ is much higher than the voltage of the initial arc. Applicant has found that for reliable arc interruption the resulting current pulse should be at least 2 times and preferably more than that of the arc current. More preferably still, the absolute value of current pulse should be in the range of from about 15 to 20 times the magnitude of the arc current.

The moment of capacitor discharge is preferably determined as follows:

In the case of an arc interruption of rated current, (the normal situation) the capacitor is preferably discharged based essentially on the load demand, i.e. when it is desired to transfer energy from the inductor **L** to the load. In the case of arc interruption of a short circuit current fault, a situation exists which gives rise to currents which may be many times greater than the rated current of the capacitor $C_1$. In this situation, the capacitor $C_1$ is preferably discharged at or near a natural zero (i.e. a zero crossing transient) of the (DC) current. This will ensure the current impulse will be

sufficiently large (in comparison to the instantaneous arc current at the moment of capacitor discharge) that an arc extinguishing arc-dipole will be reliably formed.

Usually, a capacitor having a high dielectric voltage is needed to interrupt a high voltage. But in order to use existing capacitors, i.e., capacitors having relatively low dielectric voltage, for interrupting high voltages, devices such as a spiral arc breaker having metal grid plates or the like, preferably in the form of auxiliary electrode pairs or plates, may be used in the opening switch, and a transverse magnetic field may be formed in the opening switch with the capacitor voltage imposed across the auxiliary electrodes. The number of pairs of auxiliary electrodes should be determined by the appropriate interruption voltage. In the embodiment described below in connection with Fig. 9, a spiral arc is produced by the magnetic field and caused to contact the pair of auxiliary electrodes. The capacitor is then discharged through a part of the spiral arc, i.e., the portion between the pair of auxiliary electrodes.

As a result, an arc-dipole is formed in only a part of the arc. As before, the arc-dipole is caused to contract and its charged regions are caused to explosively scatter whereby

the arc-dipole part of the arc is extinguished, which results in the extinction of the arc.

The advantages of the present invention include the following:

1. The arc extinction time is very short, because the life-time of the arc-dipole is very short.

2. The dielectric recovery characteristic is very good.

3. The switch structure according to the invention is rugged, simple and reliable.

4. The method and apparatus can be easily combined with existing arc extinction methods (for instance, the above mentioned auxiliary electrode or spiral arc device).

5. This arc extinction method and apparatus may be used in a gaseous medium (such as air or $SF_6$), in a liquid medium (such as oil), or in a vacuum. When using this method in $SF_6$ or in a vacuum, the arc interrupting capability is further enhanced.

Opening Switch based on the New Arc Extinction Method

Fig. 4A is a schematic diagram and illustrates the principles of an opening switch based on the arc extinction method of the present invention. The switch comprises the spark gap SG having electrodes **1** and **2**, and a capacitor $C_1$. The spark gap **SG** serves as an opening switch. The current impulse forming circuit may comprise a voltage deviser $R_1$, $R_2$ connected across the source $PS_1$ (or a separate power source), a capacitance $C_1$ and an equivalent circuit resistance $R_3$ of the discharging circuit for the capacitor $C_1$. The capacitor $C_1$ is charged when the switch $S_1$ is in position "**a**" and in this embodiment, serves as the pulse electric power source. As will be understood by the artisan where a separate power source is used in lieu of the voltage deviser $R_1R_2$, it may be either an AC or DC source. However, where an AC source is used, the capacitor $C_1$ will need to be charged through a diode (not illustrated). The polarity of the charged condenser **C** need not be identical with polarity of the electric power. It is for this reason that the present method and apparatus can be used for arc interruption in either an AC or DC circuit. The spark gap may be a self break down gas gap or a triggered spark gap.

Assuming the electrodes **1** and **2** are spaced apart by a gap distance sufficiently small to sustain an arc discharge, then the energy storing circuit for the inductance **L** is closed through the arc produced between the contacts **1** and **2**. When it is desired to transfer the energy from the inductance **L** to the load, a voltage, preferably a pulsed voltage, is produced (the capacitor **C** being its source in this embodiment) and is imposed between the electrodes **1** and **2**. At this time, the arc-dipole is formed and the arc is extinguished by the above-mentioned process.

Fig 4B is similar to Fig. 4A except that spark gap having a magnetic field producing means **22** is also used. The magnetic field acts on the arc in order to form an arc-dipole of greater charge gradient $g_d$. As explained above, the use of a magnetic field is optional and, especially in relatively low voltage situations, may not be required for effectively transferring current to the load.

A timing relay may be used to determine the moment when the voltage is imposed across the contacts **1** and **2**. In the case of interruption of rated current this moment occurs when the energy transfers to the load is desired. In the case of interruption of a short circuit current or high voltage AC, this moment is ideally when the current waveform passes

through a natural zero. The time that the relay switches the switch $\mathbf{S_2}$, i.e., after the interruption of an arc current, in order to interrupt the current flowing through capacitor $\mathbf{C_1}$ from the inductance **L** and to recharge the capacitor $\mathbf{C_1}$ is determined by the circuit described below in connection with Fig. 4D.

Fig. 4B is similar to Fig. 4A except that the voltage divider network $\mathbf{R_3}$ and $\mathbf{R_4}$ is used to charge the capacitor $\mathbf{C_1}$ from the power supply $\mathbf{PS_1}$, eliminating the need for the power supply $\mathbf{PS_2}$.

Fig. 4C is another embodiment of an opening switch according to the present invention. With switch $\mathbf{S_1}$ open and switch $\mathbf{S_{12}}$ open, and the opening switch **OS** conducting, energy is stored in the inductance **L** and at the same time the capacitor $\mathbf{C_1}$ is charged. When it is desired to transfer an energy pulse to the load **20**, the switches $\mathbf{S_{11}}$ and $\mathbf{S_{21}}$ are closed. Closing the switch $\mathbf{S_{11}}$ places the voltage across the capacitor $\mathbf{C_1}$ across the spark gap **SG** and provides a path for a current impulse to flow from the capacitor $\mathbf{C_1}$, through the spark gap **SG** and resistor $\mathbf{R_1}$. If the above described current impulse criteria are met, the current impulse will create an arc dipole in the spark gap SG causing it to open the charging current for the inductor **L**, essentially instantaneously, most

preferably in 2μs or less. As will be appreciated by the artisan this will result in the energy stored in the inductor **L** ($\frac{1}{2}LI_o^2$) to be transferred to the load **20**. Ideally, almost all of the stored energy will be transferred if the current cut off through the spark gap **SG** is fast enough. If the current cut off time of the spark gap is too slow, some of the stored energy in the inductor will be dissipated.

Although the various embodiments of the invention described above use a capacitor as the current impulse source to create an arc dipole, the invention is not so limited and any switchable impulse current source can be used to inject an impulse current into the spark gap to interrupt the arc. To realize the benefits of the invention, the impulse current should have a magnitude (absolute value) of at least two times the arc current. Of course, the magnitude of the current pulse can be even greater than 2 times the arc current as long as it is physically sustainable by the circuit (and is not cost prohibitive to realize). Applicant has found that with current impulses having an absolute value about 20 times the magnitude of the arc current, current cut off times in the sub microsecond range can be achieved.

This should be contrasted with the artificial zero current used in the past to extinguish arcs where a current

equal in magnitude and opposite in polarity to the arc current were used to extinguish an arc by artificially creating a "0" current. In contrast, that method is generally less reliable and results in possible reignition damages since the charged plasma remains in place between the spark gap electrodes.

In the above described embodiments, the switch $\mathbf{S_{11}}$ and $\mathbf{S_{21}}$ are preferably ganged or otherwise synchronized, e.g. electronically for simultaneous or at least near simultaneous operation. When the switch $\mathbf{S_{11}}$ is in the position to charge capacitor $\mathbf{C_1}$ (position "**a**" in Figs. 4A and 4B) the switch $\mathbf{S_{21}}$ is in its open position. When the switch $\mathbf{S_{11}}$ is in position to deliver a current impulse to the opening switch (position "**b**" in Figs. 4A and 4B) the switch $\mathbf{S_{21}}$ should be closed. By appropriate control of the switches $\mathbf{S_{11}}$ and $\mathbf{S_{21}}$, the invention can be used to deliver a periodic train of power pulses, e.g. at 1 kpps or on demand pulses. While a 1 kpps power pulses supply is adequate for most applications, i.e., loads such as for example a industrial tools or plasma furnaces, other loads may require much faster pulse repetition rates, i.e. on the order of $10^4$-$10^5$ hz, which also are achievable with the present invention.

Where the pulses are used to cause temperature increases, the energy W required to raise the temperature T is proportional to the energy per pulse.

Referring now to Fig. 5, it should appreciated the pulse power is a function of the current through and voltage across the load (V·I). For a train of pulses, the total power delivered is simply to sum total of per pulse power.

$$\text{Power} = \sum_{1}^{n} V\cdot I \qquad \text{(e.g. 2)}$$

Thus, the energy (E) delivered is $\sum_{1}^{n} V\cdot I\ \Delta T$ where $\Delta T$ is the pulse length duration. With respect to the embodiments of Fig. 4A, 4B and 4C, it should be appreciated that the speed of the spark gap **SG** is not subject to the speed of the operation of switch $\mathbf{S_{11}}$. With reference to Fig. 5B, and assuming the operation of switch $\mathbf{S_{11}}$ at time $\mathbf{t_1}$ but that no current pulse was injected into the spark gap **SG** until time $\mathbf{t_2-t_1}$, and a current $\mathbf{I_o}$ continues to flow through the spark gap **SG**, no discernable effect would be presented in terms of the effectiveness, reliability or speed of the opening switch. The important time increment is $\delta t$, the time it takes for the current through the opening switch to transition form $\mathbf{I_o}$ to **O**. That time should be less than about 2µs and preferably less

than about 1μs. More preferably still, for efficient transfer of large quantities of energy, complete current cut off through the opening switch should be accomplished in a sub microsecond time increment. In other word, the important opening switch parameter is the time it takes to extinguish the arc between the normally open contacts or electrodes of the spark gap **SG**.

Fig. 7A, 7B and Fig. 9 depict embodiments of the opening switch wherein a magnetic field is used to affect the formation of the arc-dipole.

Fig. 7A is an embodiment wherein the switch is encased in a ceramic container **40** which contains a dielectric medium (such as a vacuum or $\mathbf{SF_6}$ gas). Reference numerals **1** and **2** denote the spark gap electrodes (there may also be a trigger electrode), reference numeral **36** denotes a support cylinder for the electrodes and reference numeral **38** denotes a spiral blade formed on the side surface of the support cylinder **36**. Reference numerals **40** and **42** denote wires which directly link the electrodes **1** and **2** to the arc dipole formation circuit and to the load. Reference numeral **48** denotes an insulating material.

The operation of the basic switch has been explained above in connection with Figs. 4A, 4B and 4C. The axial

magnetic field is produced by the current flowing through the spiral blade made on the side surface of the cylindrical member **36** associated with the electrodes **1** and **2**. (See Fig. 8A and Fig. 8B). This switch is suitable for use as an opening switch for medium voltages, such as voltages in the range of from about 3kv to 50kv.

In the circuit of Fig. 7A the magnetic field is axial, i.e., in the direction of the arc current. In the embodiment of Fig. 7B, the spiral blades are designed so that in the region of the arc, the magnetic field is transverse to the direction of arc current flow. This is accomplished by producing the screw threads **38** so that the surface current flows in opposite (in the sense of clockwise/counterclockwise) directions in the cylinder parts associated with the electrodes **1** and **2** respectively.

The pitch of the threads should be as small as possible so that the surface current will flow through as many "turns" as possible.

The transverse or rotary magnetic field will cause the arc to take a transverse or rotary direction. This is preferred when the switch is operated in air in order to reduce the tendency of an arc to remain stationary, i.e. on

the same spot on the disc shaped contact piece, and cause a hot spot (or pit) to be created.

Fig. 8A illustrates the structure of the electrode pieces of Figs. 7A and 7B for producing a magnetic field. The function of producing magnetic field usually supplied by a coil. In this case, a spiral blade formed on the side surface of the electrode pieces (which are preferably of a generally cylindrical shape) is used. The current flowing through the blades is determined by the ratio between the radial dimensions of $\mathbf{S_1}$ and $\mathbf{S_2}$ in the cross-section of the cylindrical member associated with the contact piece. The screw blade may be formed on both the outside and inside of the cylindrical member associated with the contact pieces or only on one surface. If both surfaces are used, it is equivalent to a coil having two layers. The pitch of the screw is made as small as possible in order to decrease the volume of the contact piece assembly.

Fig. 8B illustrates the A-A' cross-section of the contact S1 is the cross-section of the cylindrical contact, and S2 is the cross-section of the screw blade. The ratio of current is

$$\gamma = S_2/S_1 \qquad \text{(e.g. 3)}$$

This is the ratio of the surface current to the total current flowing through the cylindrical contact pieces. The

higher the value of $\gamma$, the higher the magnetic field produced for a given number of "terms", i.e., the pitch times the axial length of the contact piece.

Fig. 9 illustrates an embodiment of a medium or high voltage opening switch in which the arc dipole methodology is combined with spiral arc methodology. In the illustrated embodiment, the medium used is air. A vacuum or $SF_6$ gas or other gaseous or liquid dielectric may also be used. In the illustrated embodiment, where the medium is air, a conductive cylindrical member **38** is used to produce an transverse magnetic field. The magnetic field **38** producing structure and associated electrodes **1** and **2** are coaxially mounted about a pair of metal plates **44** and **45** or auxiliary electrodes, which are used in conjunction with the spark gap electrodes **1** and **2.** As indicated by the dashed lines within the members **46,** the opening switch is connected to the current impulse forming circuit at a pair of metal plates **44** and **45**. The magnetic field producing means is similar to that illustrated and described about in connection with Fig. 8B. The structures indicated **1** and **2** are essentially the same as those used in Figs. 7A and 7B. Reference numeral **46** denotes a rod made of insulating material and reference numeral **47** denotes a spiral arc between the electrodes **1** and **2.**

A spiral arc, produced by the force of the transvers magnetic field, exists between the pair of normally open electrodes **1** and **2**. A part of that arc extends between the plates or auxiliary electrodes **44** and **45**. It is in this portion of the arc that the arc dipole is created, thus, extinguishing the arc.

The foregoing descriptions of the presently preferred embodiments of the invention have been presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, and obviously many modifications and variations are possible in light of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto.

## Claims

1. A method of producing an energy pulse to a load in a load circuit by opening an arc between a pair of opposed, normally open electrodes connected to said load circuit, said method comprising:

causing an arc to be created between said electrodes thereby completing the load circuit,

creating a charge gradient in at least a portion of the arc between said electrodes, whereby an arc-dipole is formed; and

using said arc dipole to extinguish the arc.

2. The method according to claim 1 wherein said arc-dipole includes a region of net positive charged particles and a region of net negative charged particles, each created in a space adjacent an electrode and further comprising the step of using said arc-dipole to explosively scatter the positive and negative charged particles thereby creating an essentially charged-particle-free space adjacent said electrodes, said essentially charged-particle-free space acting as a dielectric medium between said electrodes.

3. The method according to claim 1 wherein said step of creating a charge gradient further comprises imposing an electric field across said contacts.

4. The method according to claim 3 further comprising the step of simultaneously imposing a magnetic field in the region of said arc; and

applying said magnetic field to at least a region of said arc to enhance the charge gradient, $g_d$, along said arc-dipole.

5. The method according to claim 4 wherein said step of applying a magnetic field further comprises imposing an axial magnetic field between said electrodes, said magnetic field operating in a direction to confine the radial expansion of said arc.

6. The method according to claim 4 wherein the step of applying a magnetic field further comprises imposing a transverse magnetic field between said contacts whereby the arc is caused to move with respect to the surface of said contacts.

7. The method according to claim 3 wherein said arc has a characteristic relaxation time, $\tau$, and said step of creating a charge gradient further comprises the step of injecting a current pulse through said arc in a time much shorter than said characteristic relaxation time.

8. The method according to claim 3 wherein said step of imposing said electric field comprises discharging a pre-charged capacitor through at least a portion of said arc.

9. The method according to claim 7 wherein said arc has an arc current of a given magnitude and wherein the step of injecting a current pulse further comprises the step of using said electric field to create a current pulse in said arc, said current pulse having an absolute value much greater than the magnitude of said arc current.

10. The method according to claim 9 wherein said current pulse flows in the same direction as said arc current.

11. The method according to claim 9 where said current pulse flows in the opposite direction to said arc current.

12. The method according to claim 1 wherein said arc has an arc current, said arc current being DC.

13. The method according to claim 1 wherein said arc has an arc current, said arc current being AC.

14. The method according to claim 13, wherein said step of creating a charge gradient further comprises the step of injecting a current pulse into said arc, at or near a zero crossing of said AC cycle.

15. The method according to claim 9 further comprising the step of discharging a pre-charged capacitor to generate said current pulse.

16. The method according to claim 2 wherein said electrodes comprise at least one auxiliary electrode positioned in said arc between said pair of opposed electrodes.

17. The method according to claim 2 wherein said arc is extinguished on the order of less than about 2 μs after said arc-dipole is formed.

18. The method according to claim further comprising the step of delivering a train of pulses to said load.

19. An opening switch for producing a power pulse to a load in a load circuit comprising:

a spark gap comprising normally open first and second electrodes, said spark gap being connected to said load circuit;

a power source for causing an arc to form between said electrodes;

a pulsed power source for injecting a current pulse into said arc, said power source being operable to create an arc-dipole in at least a portion of said arc, thereby

extinguishing said arc and transferring energy from said power source into said load circuit.

20. The opening switch according to claim 19 wherein said spark gap is connected between said power source and said load circuit and further comprising a charging circuit for pre-charging said capacitor.

21. The opening switch according to claim 19 further comprising a discharge circuit for discharging said capacitor through said electrodes in a time period short as compared to the relaxation time of said arc.

22. The switch according to claim 19 wherein said discharge creates said arc-dipole in at least a portion of said arc, whereby said arc is axially contracted and essentially charged particle free spaces are created at the end regions of said arc-dipole.

23. The switch according to claim 19 wherein said arc has an arc current of a given magnitude and said current pulse has an absolute value of at least about two times the magnitude of said arc current.

24. The opening switch according to claim 19 further comprising a magnetic field generating means for establishing a magnetic field in the region of said arc, said magnetic field operating in a direction to tend to confine said arc

from expanding in its radial direction whereby the charge gradient of said arc-dipole is enhanced.

25. The switch according to claim 19 further comprising a magnetic field generating means for establishing a magnetic field in the region of said arc, said magnetic field operating in a direction generally transverse to said arc.

26. The switch according to claim 19 further comprising means for extending the axial length of said arc between said first and second contacts wherein said arc-dipole is created in a portion of the arc.

27. The opening switch according to claim 19 wherein said switch operates in air.

28. The opening switch according to claim 19 wherein said switch operates in a vacuum.

29. The opening switch according to claim 19 wherein said switch operates in $SF_6$ gas.

30. The opening switch according to claim 19 wherein said switch operates in a dielectric liquid.

31. The opening switch according to claim 19 wherein the rise time of the current pulse is less than about 2 μs.

32. The opening switch according to claim 19 wherein said pulsed power source is connected across said electrodes.

33. The switch according to claim 19 further comprising a pair of auxiliary electrodes positioned in the region of said arc and between said first and second electrodes and wherein said pulsed power sources is connected across said auxiliary electrodes.

34. An opening switch for producing a power pulse to a load circuit comprising:

first and second electrodes, said electrodes being connected between a power source and a load;

means to strike an arc between said electrodes, thereby closing a part of said load circuit;

a discharge electrode spaced from one of said first and second electrodes;

a normally open auxiliary switch connected in series with said electrodes and said load;

a pulse power source for injecting a current pulse into an arc formed between said first and second electrodes, said current pulse being injected via said discharge electrode, said pulse power source being operable to create an arc-dipole in at least a portion of said arc;

said auxiliary switch being operable to close upon creation of said arc-dipole to thereby transfer a current pulse to said load.

35. The opening switch according to claim 34 wherein said pulse power source comprises a capacitor connected to discharge upon initiation of said arc, and further comprising a charging circuit for pre-charging said capacitor from said power source.

36. The opening switch according to claim 35 further comprising a discharge circuit for discharging said capacitor in a time period short as compared to the relaxation time of said arc.

37. The opening switch according to claim 36 wherein said discharge creates said arc-dipole in said arc, whereby said arc-dipole is axially contracted and an essentially charged-particle-free region is created at an end region of said arc dipole.

38. The opening switch according to claim 37 wherein said auxiliary switch is adapted to close after the creation of said essentially charged-particle-free region.

39. The opening switch according to claim 35 wherein said arc-dipole exhibits a characteristic charge gradient $g_a$ and further comprising a means for producing a magnetic field adjacent said arc simultaneously with the injection of said current pulse, said magnetic field being operable to enhance the charge gradient $g_d$.

40. The opening switch according to claim 39 wherein said means for producing a magnetic field comprises a coil positioned adjacent said arc.

41. The opening switch according to claim 39 wherein said first and second electrodes comprises generally flat disc shaped conductor elements, at least one of said electrodes having a generally cylindrical conductive member in electrical contact therewith, and wherein said means for forming said magnetic field comprises a generally helical thread on said generally cylindrical conductive number for conducting surface current along a generally helical path to thereby create said magnetic field.

42. The opening switch according to claim 41 wherein each of said electrodes has a generally helically threaded, generally cylindrical, conductive body associated therewith, said generally helical threads being oriented to form a magnetic field which is generally axial with respect to the direction of current flow between said electrodes.

43. The opening switch according to claim 41 wherein each of said electrodes has generally helically threaded, generally cylindrical, conductive body associated therewith, the generally helical threads of said bodies being respectively oriented to form a magnetic field which is

generally transverse with respect to the direction of current flow between said first and second electrodes.

44. The opening switch according to claim 34 wherein said switch is contained with a vacuum.

45. The opening switch according to claim 34 wherein said switch is contained within a gaseous atmosphere.

46. The opening switch according to claim 34 wherein said gas is $SF_6$.

47. The opening switch according to claim 34 wherein said switch is contained in air.

48. The opening switch according to claim 34 wherein said switch is maintained in a liquid dielectric.

49. The opening switch according to any one of claims 41 or 42 wherein said generally cylindrical, conductive bodies have inside and outside surfaces along the axis of said cylinder and helical threads are formed on both the interior and exterior surfaces.

50. The opening switch according to any one of claims 41 or 42 wherein the generally helical thread are square threads and have an minimum annular radius $S_1$ and an maximum annular radius of $S_2$, and the ratio $S_1/S_2 = \gamma$ represents the ratio of surface current flowing through said generally cylindrical

conductive body to the total current flowing through said body.

51. An opening switch circuit for supplying a current pulse to a load, said circuit comprising a voltage source and a load, said voltage source having a rated voltage on the order of 10kv or more said circuit further comprising:

first and second spaced apart, opposing electrodes;

a pair of spaced apart auxiliary electrodes disposed between said first and second electrodes;

a pulsed power source switchably connected to said auxiliary electrodes for injecting a current pulse into a portion of the arc formed between said first and second electrodes to thereby create an arc-dipole in the portion said arc between said auxiliary electrodes.

52. The opening switch according to claim 50 wherein said pulse power source comprises a pre-charged capacitor connected to discharge through at least a portion of said arc via said auxiliary electrodes.

53. The opening switch according to claim 51 further comprising a charging circuit for pre-charging said capacitor.

54. The switch according to claim 51 further comprising a discharge circuit for discharging said capacitor through

said auxiliary electrodes in a time period short as compared to the relaxation time of said arc.

55. The opening switch according to claim 51 wherein said discharge creates said arc-dipole in the portion of said arc between said auxiliary electrodes, whereby said arc-dipole is axially contacted and an essentially charged-particle-free region is created adjacent at least one of said auxiliary electrodes.

56. The breaker switch according to claim 51 wherein said first and second electrodes are disc shaped and have an opening therein and said auxiliary electrodes are disc shaped, said auxiliary electrodes being coaxially positioned with said first and second electrodes are carried on non-conductive members which extend through the openings in said first and second electrodes.

57. The opening switch according to claim 51 wherein said arc has an arc current of a given magnitude and said pulsed power source is operable to inject an impulse current through a portion of said arc, said impulse current having an absolute value of at least about two times the magnitude of said arc current.

58. The opening switch according to claim 51 further comprising a magnetic field generating means for establishing

a magnetic field in the region of said arc simultaneously with the creation of said arc, said magnetic field having a direction which tends to confine said arc-dipole from expanding in its radial direction whereby the charge gradient of the arc-dipole between said auxiliary contacts is enhanced.

59. The breaker switch according to claim 51 further comprising a magnetic field generating means for establishing a magnetic field in the region of said arc simultaneously with the creation of said arc, said magnetic field having direction transverse to the direction of said arc between said auxiliary contacts.

60. The opening switch according to claim 51 wherein said switch operates in air.

61. The opening switch according to claim 51 wherein said switch operates in a vacuum.

62. The opening switch according to claim 51 wherein said switch operates in $SF_6$ gas.

63. The opening switch according to claim 51 wherein said switch operates in a dielectric liquid.

64. The opening switch according to claim 56 wherein at least one of said first and second comprises a disc-shaped electrod piece having a generally helically threaded, generally cylindrical, conductive body associated therewith,

said generally helical threads being so oriented that when a surface current flows thereon, a magnetic field is formed which is generally axial with respect to the direction of arc current flow between said first and second electrodes.

65. The opening switch according to claim 56 wherein each of said first and second electrodes comprises a generally disc shaped contact piece having a generally helically threaded, generally cylindrical, conductive body associated therewith, the generally helical threads of said generally cylindrical conductive bodies being oriented to form a magnetic field which is generally transverse with respect the direction of current flow between said first and second contacts.

66. The opening switch according to claim 64 wherein said generally cylindrical, conductive body has inside and outside surfaces along the axis of said cylinder and helical threads are formed on both the interior and exterior surfaces thereof.

67. The opening switch according to claim 65 wherein each of said generally cylindrical, conductive bodies has inside and outside surfaces along the axis of said cylinder and said helical threads are formed on both the interior and exterior surfaces thereof.

68. The opening switch according to any one of claims 64 or 65 wherein the generally helical thread are square threads and have an minimum annular radius $S_1$, and an maximum annular radius $S_2$ and the ratio $S_1/S_2 = \gamma$ represents the ratio of surface current flowing through said generally cylindrical conductive body to the total current flowing through said body.

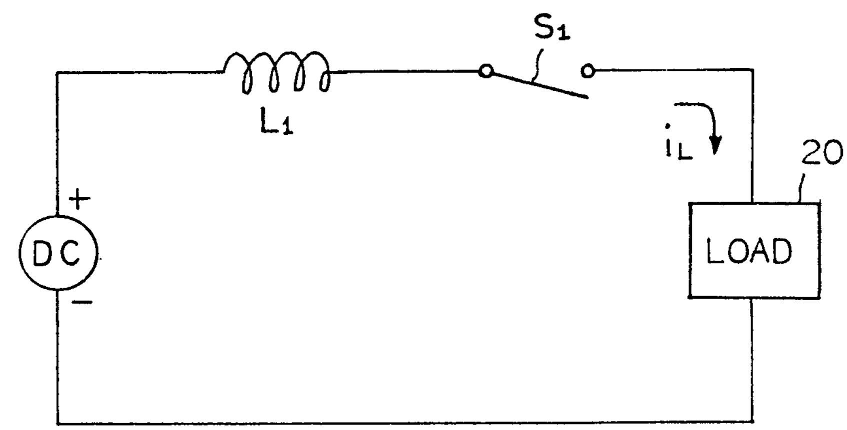



FIG. 1A

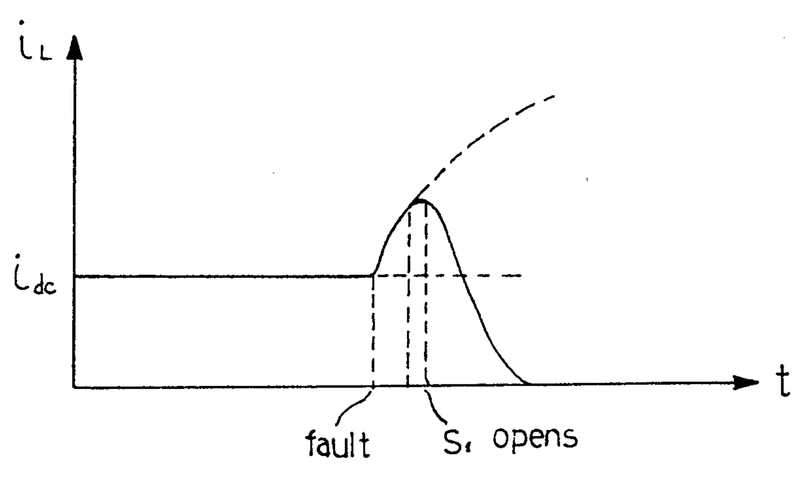



FIG. 1B

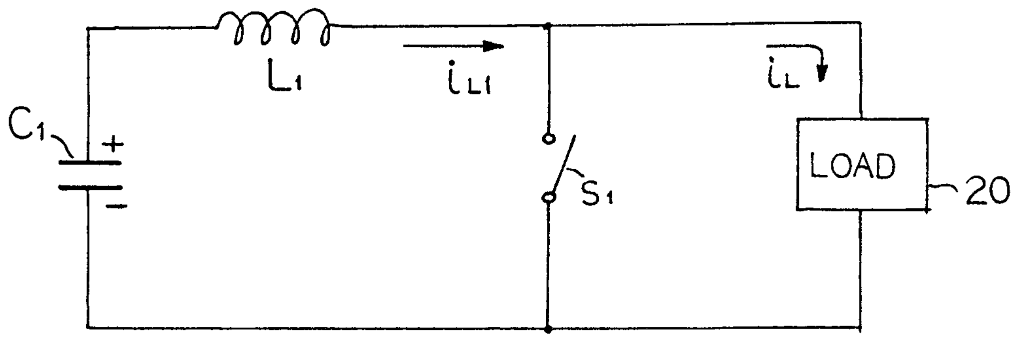



FIG. 2A

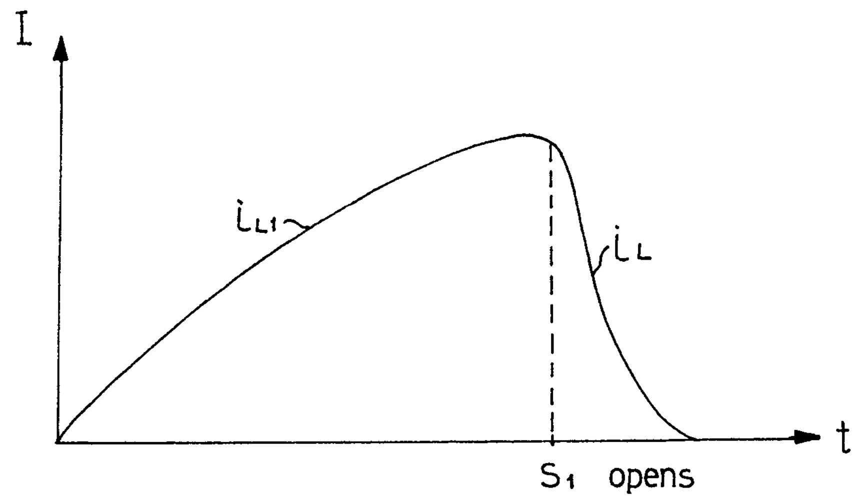



FIG. 2B

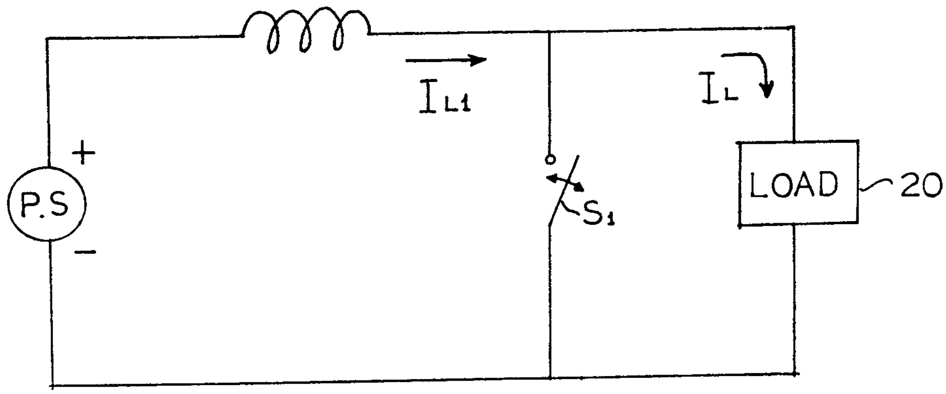



FIG. 3A

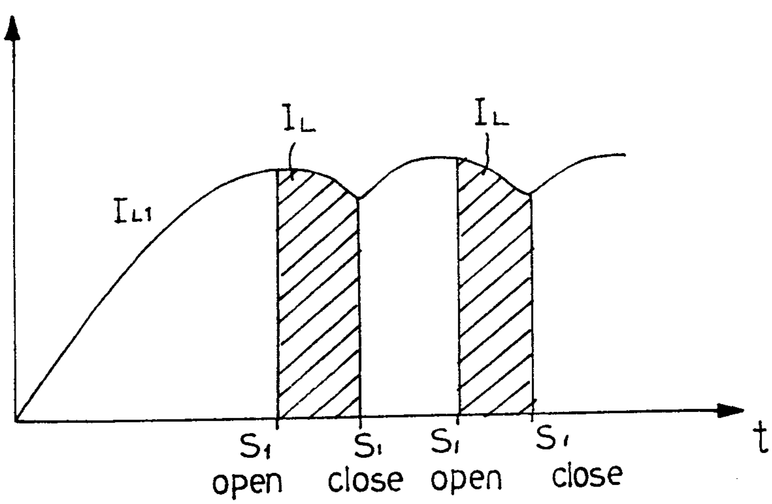



FIG. 3B

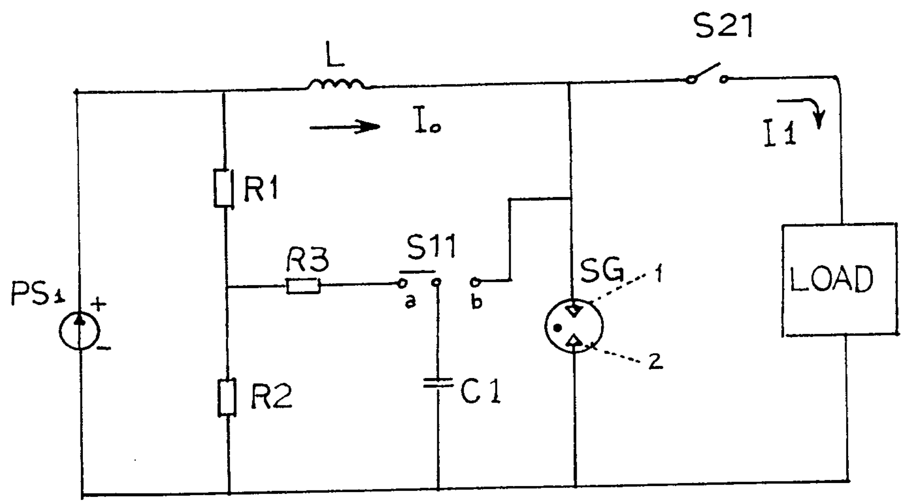

S21
L
I₀
I1
R1
R3
S11
SG
1
LOAD
PS1
+
-
a
b
2
R2
C1

FIG. 4A

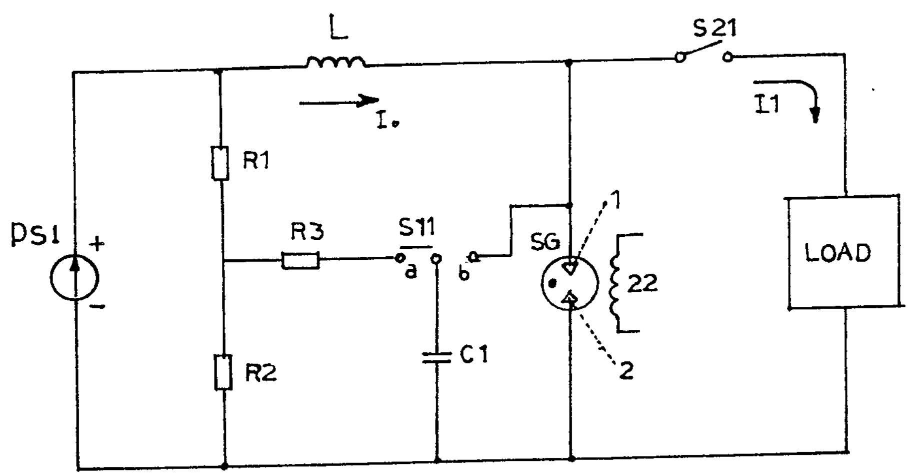

L
S21
I₀
I1
R1
1
R3
S11
SG
PS1
+
-
a
b
22
LOAD
R2
C1
2

FIG. 4B

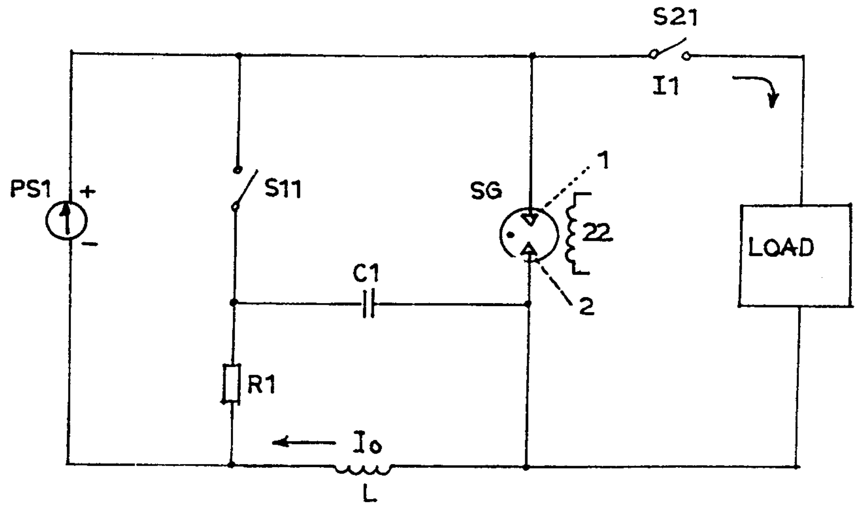

S21
I1
PS1
+
-
S11
SG
1
22
LOAD
C1
2
R1
Io
L

FIG. 4C

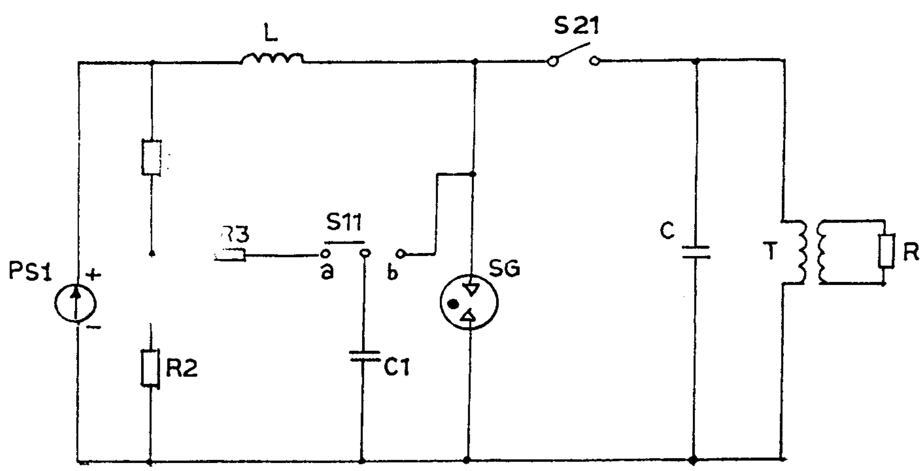

L
S21
R3
S11
a
b
SG
C
T
R
PS1
+
-
R2
C1

FIG. 4D

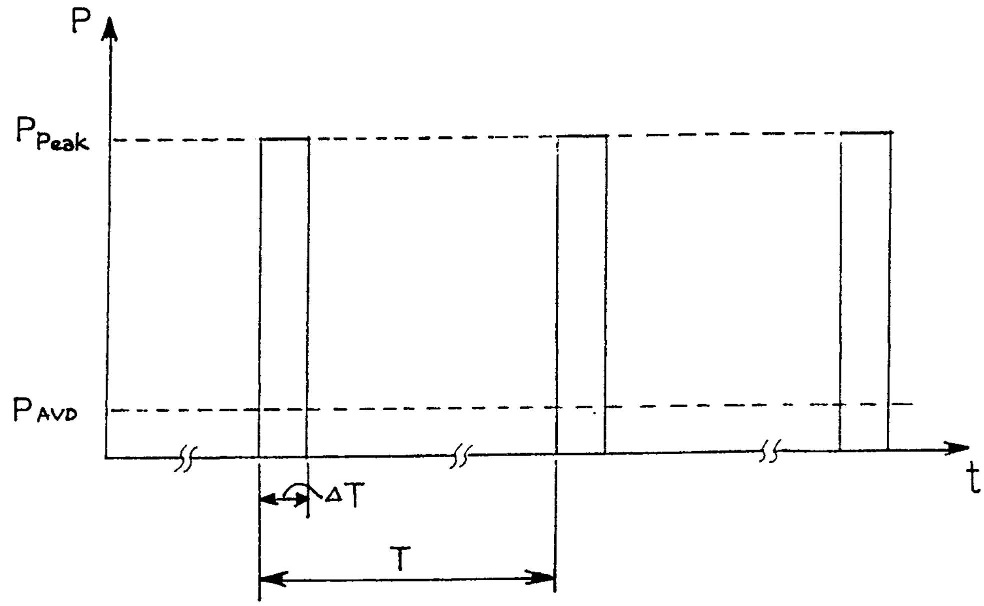



FIG.5A

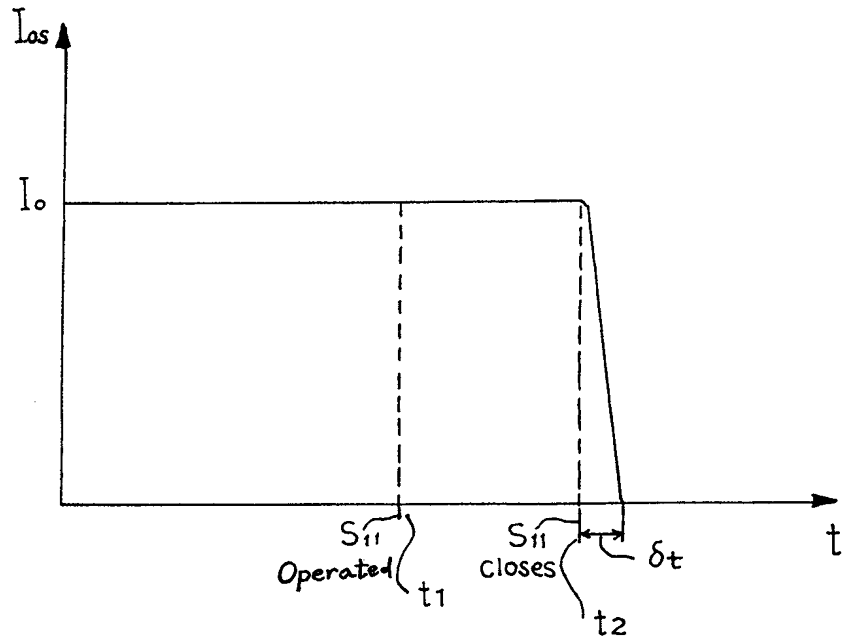



FIG.5B

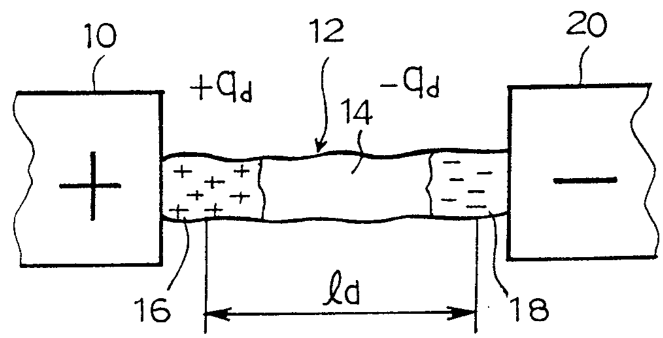



FIG.6

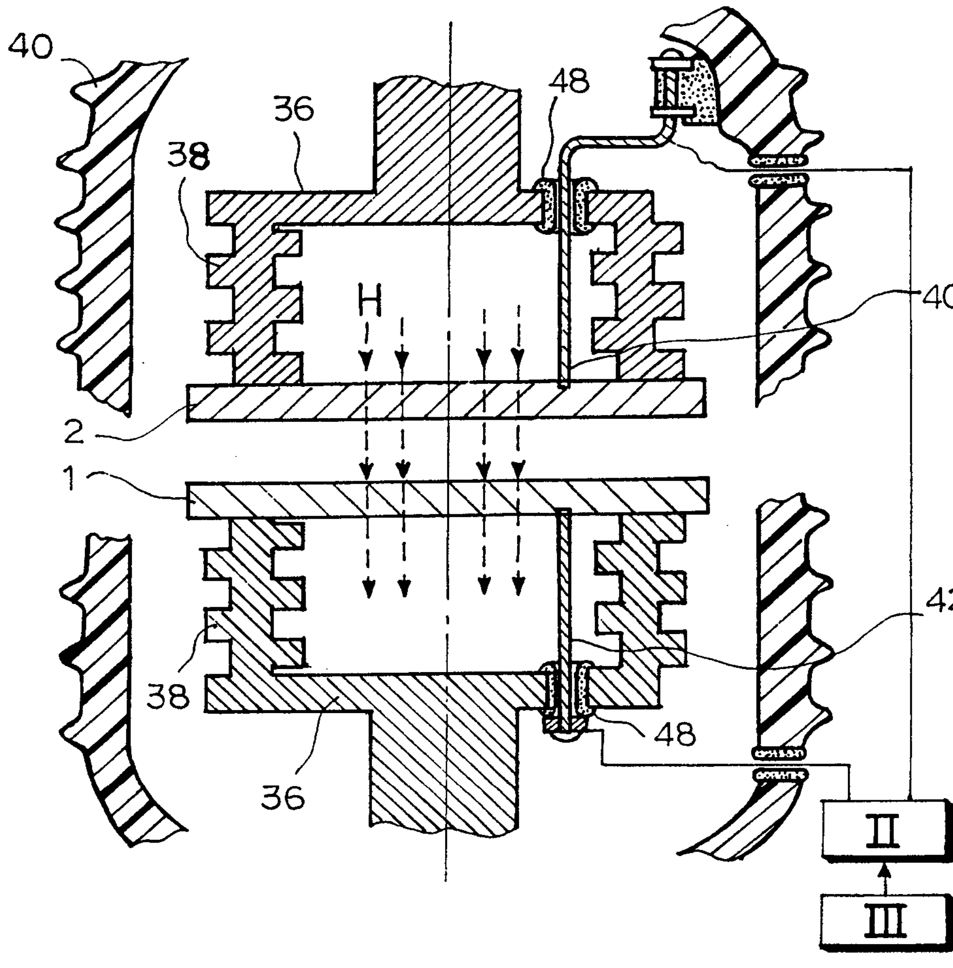



FIG. 7A

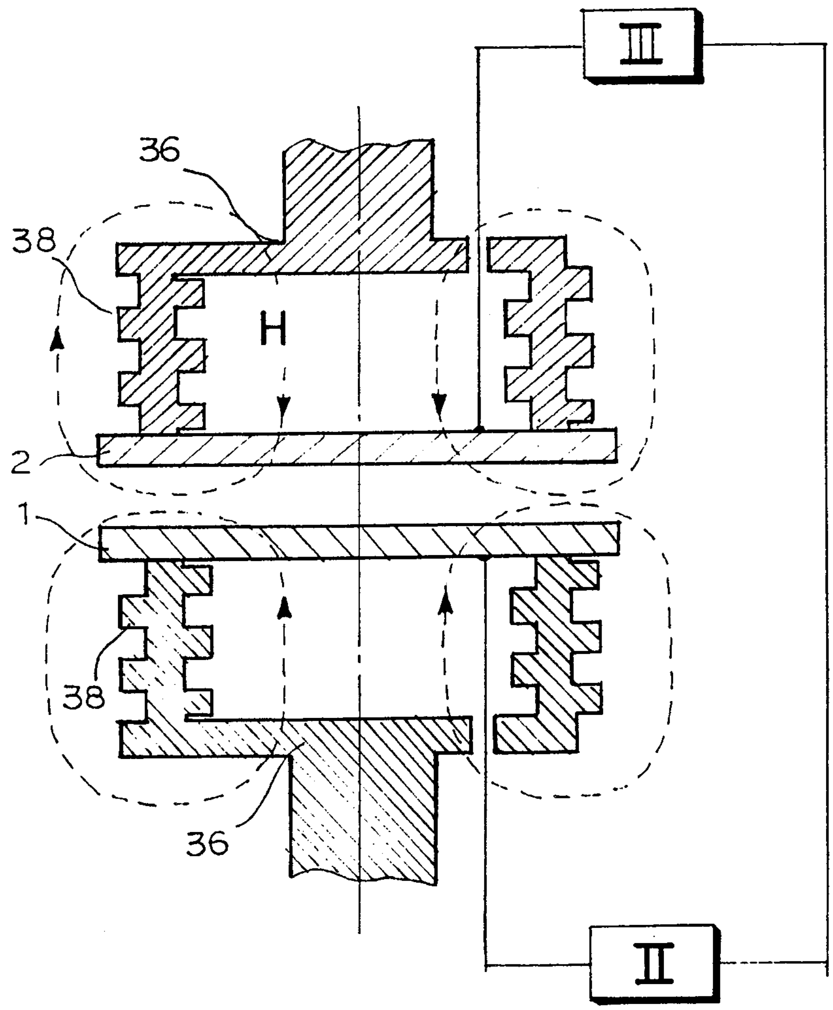



FIG.7B

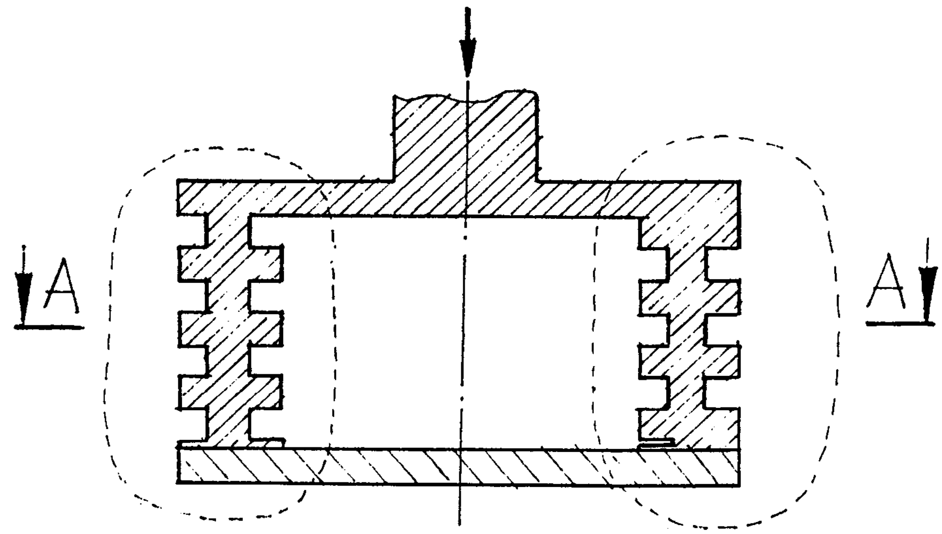



FIG.8A

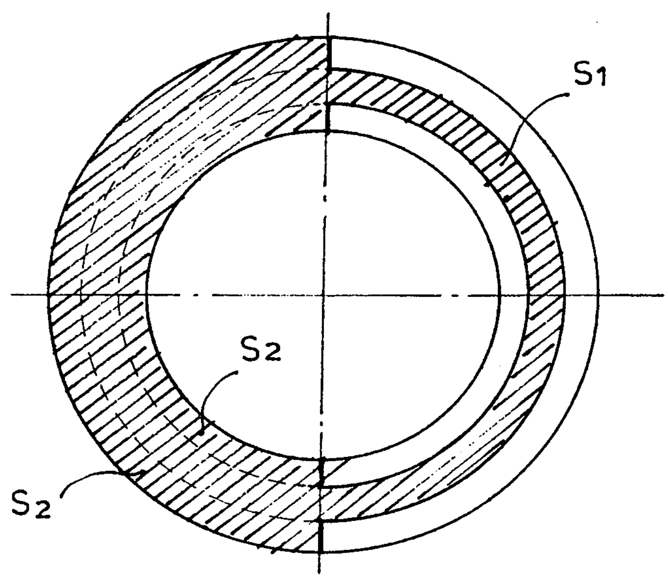



FIG.8B

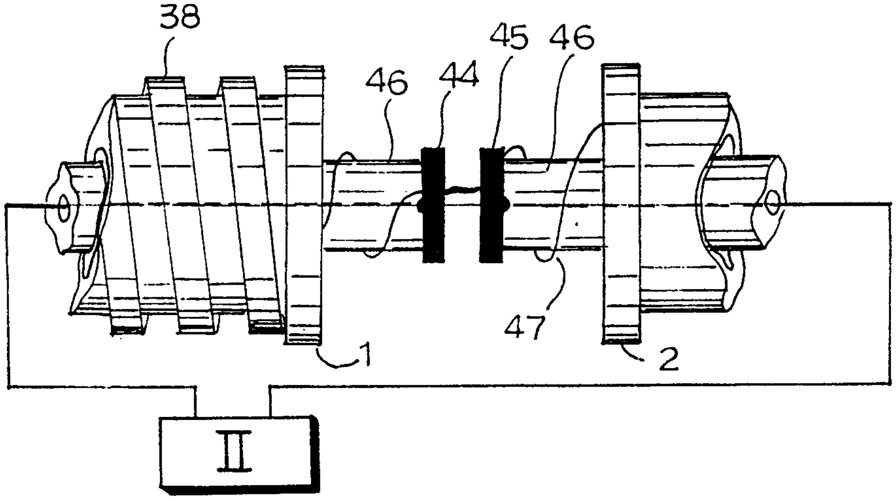



FIG.9

# INTERNATIONAL SEARCH REPORT

I. ..ional Application No
PCT/IB 97/01394

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 6 H01T1/02

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01H H01T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | GREENWOOD A N ET AL: "Theory and application of the commutation principle for HVDC circuit breakers" IEEE TRANSACTIONS ON POWER APPARATUS AND SYSTEMS, JULY-AUG. 1972, USA, vol. PAS-91, no. 4, ISSN 0018-9510, pages 1570-1574, XP002049258 cited in the application see the whole document --- | 1 |
| A | US 5 568 019 A (R.J.MASON) 22 October 1996 see abstract --- | 1 |
| A | GB 828 865 A (A. VANG) 24 February 1960 see page 1, line 41 - page 2, line 25 --- | 1 |
| | -/-- | |

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 7 July 1998 | 14/07/1998 |

| Name and mailing address of the ISA | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,<br>Fax: (+31-70) 340-3016 | Libberecht, L |

2

Form PCT/ISA/210 (second sheet) (July 1992)

# INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 97/01394

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

| Category ° | Citation of document, with indication,where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | EP 0 125 553 A (MITSUBISHI ELECTRIC CORP) 21 November 1984<br>see abstract<br>& US 4 560 848 A<br>cited in the application | 4-6 |
| A | DE 32 19 268 A (SIEMENS AG) 24 November 1983<br>see the whole document | 4-6 |
| A | SCHOETZAU H J ET AL: "A NEW APPROACH TO HIGH-POWER ARC DYNAMICS"<br>EUROPEAN TRANSACTIONS ON ELECTRICAL POWER ENGINEERING,<br>vol. 4, no. 2, 1 March 1994,<br>pages 89-99, XP000454532<br>see page 97, left-hand column, paragraph 8 | 1,7 |

2

# INTERNATIONAL SEARCH REPORT

Information on patent family members

Ir. onal Application No
PCT/IB 97/01394

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|---|---|---|---|
| US 5568019 A | 22-10-1996 | NONE | |
| GB 828865 A | | NONE | |
| EP 0125553 A | 21-11-1984 | JP 59205118 A | 20-11-1984 |
| | | JP 59228321 A | 21-12-1984 |
| | | CA 1249003 A | 17-01-1989 |
| | | DE 3474081 A | 20-10-1988 |
| | | US 4560848 A | 24-12-1985 |
| DE 3219268 A | 24-11-1983 | NONE | |